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Modeling the process and costs of fuel ethanol production by the corn dry-grind process

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Abstract

The corn dry-grind process is the most widely used method in the U.S. for generating fuel ethanol by fermentation of grain. Increasing demand for domestically produced fuel and changes in the regulations on fuel oxygenates have led to increased production of ethanol mainly by the dry-grind process. Fuel ethanol plants are being commissioned and constructed at an unprecedented rate based on this demand, though a need for a more efficient and cost-effective plant still exists.

A process and cost model for a conventional corn dry-grind processing facility producing 119 million kg/year (40 million gal/year) of ethanol was developed as a research tool for use in evaluating new processing technologies and products from starch-based commodities. The models were developed using SuperPro Designer® software and they handle the composition of raw materials and products, sizing of unit operations, utility consumptions, estimation of capital and operating costs, and the revenues from products and coproducts. The model is based on data gathered from ethanol producers, technology suppliers, equipment manufacturers, and engineers working in the industry. Intended applications of this model include: evaluating existing and new grain conversion technologies, determining the impact of alternate feedstocks, and sensitivity analysis of key economic factors. In one sensitivity analysis, the cost of producing ethanol increased from US\$ 0.235 l^{-1} to US\$ 0.365 l^{-1} (US\$ 0.89 gal^{-1} to US\$ 1.38 gal^{-1}) as the price of corn increased from US\$ 0.071 kg^{-1} to US\$ 0.125 kg^{-1} (US\$ 1.80 bu^{-1} to US\$ 3.20 bu^{-1}). Another example gave a reduction from 151 to 140 million l/year as the amount of starch in the feed was lowered from 59.5% to 55% (w/w).

This model is available on request from the authors for non-commercial research and educational uses to show the impact on ethanol production costs of changes in the process and coproducts of the ethanol from starch process.
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Keywords: Corn; Ethanol; Dry-grind; Coproducts; Economics

1. Introduction

The corn dry-grind process is the most widely used method in the U.S. for generating fuel ethanol by fermentation of grain. Increasing demand for domestically produced fuel and changes in the regulations on fuel oxygenates have led to increased production of ethanol mainly by the dry-grind process. Fuel ethanol plants are being commissioned and constructed at an unprecedented rate based on this demand, though a need for a more efficient and cost-effective plant still exists.

Research towards developing new, valuable coproducts and more efficient processing technologies aim to reduce the overall cost of producing ethanol (Bothast

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and Schlicher, 2005; Rajagopalan et al., 2005). The feasibility of producing these coproducts or using new processing steps is currently evaluated by performing calculations that scale-up benchtop or pilot plant operations. The producer accepts the risks of attempting and evaluating a given processing technology. Even the reduction in cost of a few cents per liter of ethanol produced, is significant when dealing with the dry-grind process, and the ability to accurately predict the costs of production prior to incorporating new technologies is highly desirable.

Computer simulations to model and predict the costs of production have been used with success for many industrial processes. They provide the ability to estimate the effect of increasing costs of raw materials or utilities, variations in material composition, and the incorporation of new technologies. Beginning with a base-case scenario and designing the model to simulate those conditions effectively allows the user to estimate results of alternative processes with confidence. Previously models of the dry-grind ethanol from corn process (McAloon et al., 2000; Taylor et al., 2000) were developed using a combination of Aspen Plus® (Aspen Technologies Inc., Cambridge, MA) and Microsoft Excel® (Microsoft Corporation, Redmond, WA). A new model for a 150 million l/year (40 million gal/year) plant has been developed using SuperPro Designer® Version 5.5 Build 18 (Intelligen Inc., Scotch Plains, NJ), a simulation program that is able to estimate both process and economic parameters. The following is a description of this model along with analyses to determine the effect of changing corn cost and starch composition.

2. Process model description

A simplified flow diagram of the process is shown in Fig. 1. The actual process contains more than 100 pieces of equipment and unit operations. It is not intended to replicate any fuel ethanol plant in existence, but rather a generic plant design containing equipment and unit operations necessary to convert corn into fuel ethanol.

The process simulator (SuperPro Designer®) quantifies the processing characteristics, energy requirements, and equipment parameters of each major piece of equipment for the specified operating scenario. Volumes, composition, and other physical characteristics of input and output streams for each equipment item are identified. This information becomes the basis of utility consumptions and purchased equipment costs for each equipment item.

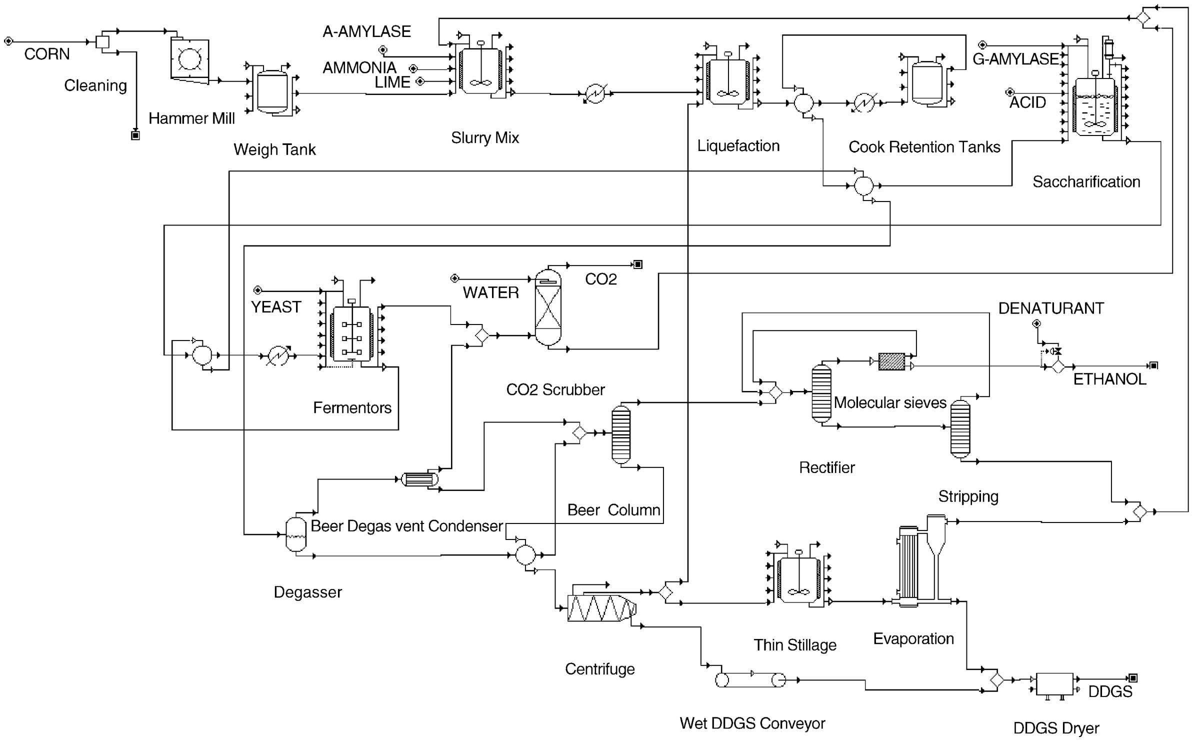

Fig. 1. Simplified flow diagram of the dry-grind ethanol from corn process.

Table 1
Composition of corn used in simulations

Component	Base-case corn (mass%)	Reduced starch corn (mass%)
Starch	59.5	55.0
Water	15.0	15.0
Non-starch polysaccharides	7.0	11.5
Other solids	6.7	6.7
Protein—insoluble	6.0	6.0
Protein—soluble	2.4	2.4
Oil	3.4	3.4

For corn, composition varies greatly by year and location, and this may be adjusted easily when declaring the composition of the feed. The nominal composition of corn used in this simulation and the composition used in the sensitivity analysis are given in Table 1. Non-starch polysaccharides are made up of corn fiber (pericarp and endosperm fiber) and other potentially valuable or fermentable components. Other solids are materials such as cleaning compounds, minerals, and other residual matter in the process. Although corn was used as the basis for this process, other agricultural products high in starch may also be input to the model, though the process may require the user to adjust the given unit operations or incorporate new operations to accommodate the new feed. The amount of material fed into the plant may be easily changed as well, allowing a user to estimate plant output based on feed availability. Based on the experimental data for composition and behavior in these unit operations, the yield of ethanol may be estimated. Table 2 gives an overview of some of the key unit operations and settings in the process model.

2.1. Grain receiving

Corn is brought into the facility and held in storage silos prior to cleaning, where broken corn, foreign objects, and finer materials are removed using a blower and screens. A portion of the stream may be recovered and added back to the distillers dried grains with solubles, but the current setting is for the broken corn and foreign objects to go to waste. These silos are sized to hold sufficient corn for 12 days of plant operation. The cleaned corn is ground in a hammer mill and sent through weighing tanks to control the feed rate to the process.

2.2. Liquefaction, saccharification, and fermentation

To begin this section, the measured ground corn is first sent to a slurry tank along with approximately 83,000 l/h

Table 2
Dry-grind ethanol from corn process at-a-glance

Unit ID	Description	Detail
103U	Belt conveyer	527.778 kg/(s m) Loading rate/belt width
KMT	Corn storage	259.2 h Residence time
101U	Cleaning	0.3% Removed as trash
102U	Hammer mill	0.0068 kJ/s/(kg/h) Specific power
202T	Surge tank	2 h Residence time
203T	Batch weighing	2 h Residence time
204T	Continuous weigh tank	2 h Residence time
219T	Alpha-amylase tank	0.082% (w/w) Alpha-amylase loading (db)
218T	Ammonia tank	89.723 kg/h Ammonia
224T	Lime tank	53.609 kg/h Lime
217T/TA	Slurry mix tank	0.25 h Residence time 31.1% Solids
211P	Slurry chop/recirculation pump	14.493 kJ/s Operating power
205E	Liquefaction heating	17007009.59 kJ/h Heating duty 87.8 °C Exit temperature
221T/TA	Liquefaction vessel	0.9 h Residence time 14.69% (w/w) Backset
207E	Jet cook heater	110 °C Outlet temperature
223V	Cook retention tank	0.25 h Residence time
220T	Glucoamylase tank	0.11% (w/w) Glucoamylase loading (db)
216T	Acid tank	0.061% Sulfuric Acid
222T/TA	Saccharification tank	5 h Residence time 99% Conversion of starch to glucose
414T/TP	Yeast tank	11.81 kg/h Yeast (0.008%, w/w, of mash)
404T/TA	Fermentors	68 h Residence time Six vessels, 1.9 million l each 10.8% Final ethanol concentration
402P	Fermentor recirculation pumps	0.001 kJ/s per pump
501V	Degasser	0.1 h Residence time
507E	Beer degas vent condenser	2.08 million kJ/h Cooling load
415PT	CO_2 scrubber	99.2% CO_2 in outlet
502TT	Beer column	34 Stages 21124.5 kg/h Steam in reboiler No condenser
503TT	Rectifier column	28 Stages 3356.5 kg/h Steam in reboiler Rectifier vapors routed to heat evaporator

Table 2 (*Continued*)

Unit ID	Description	Detail
504TT	Stripping column	27 Stages 664.5 kg/h Steam in reboiler No condenser
517U	Molecular sieves	<0.4% Water in product stream
515P	Molecular sieve recirculation pump	0.744 kJ/s Operating power
607T	Whole stillage tank	755,408 l 4.76 kJ/s Operating power for agitation
601U	Stillage centrifuge	1789.88 l/min Throughput 36.5% (w/w) Solids in underflow 26.25% of overflow to backset (5.8:1 slurry to backset ratio)
608T	Thin stillage tank	7 h Residence time
602U	Thin stillage evaporator	Four-effect evaporator 12,075 kg/h Rectifier vapor to drive first effect 33.9% Solids in syrup
611U	Wet DDG conveyor	2.0 MT/(h cm) Loading rate
609T	Process condensate tank	6 h Residence time 14.1 million l
606P	Process condensate pump	11.196 kJ/s Operating power
603U	DDGS dryer	0.06 kg Natural gas per kg evaporated
610U	Thermal oxidizer	3,165,168 kJ/h Heating duty
612U	DDGS conveyor handling	37.3 kJ/s Operating power
703T	Ethanol day tank	23.2154 h Residence time 433,247 l
705T	Denaturant tank	4.345% Denaturant in output ethanol
704T	Fuel ethanol product tank	155.7594 h Residence time

of process water, thermostable alpha-amylase, ammonia, and lime. Alpha-amylase is added at 0.082% (db) of corn brought to the slurry, while ammonia and lime are added at 90 kg/h and 54 kg/h, respectively. After the slurry is prepared, the mixture undergoes liquefaction, where starch is gelatinized using a "jet-cooker" (steam injection heater) and hydrolyzed (broken down) with thermostable alpha-amylase into oligosaccharides also known as dextrins. During the gelatinization step, there is a sharp rise in the slurry viscosity that is rapidly decreased as the alpha-amylase hydrolyzes the starch. Liquefaction is done at pH 6.5 and is initially held for 60 min at 88 °C with agitation. The output from the initial liquefaction step is combined with "backset", a recycled stream taken from the liquid portion of the "stillage" separated by centrifugation later in the process. The backset provides critical nutrients for the yeast later in fermentation. These combined streams are "cooked" and held at 110 °C for 15 min, and transferred to the saccharification tank after some heat is recovered using the process streams.

Further conversion of the oligosaccharides by glucoamylase to glucose is referred to as saccharification. Sulfuric acid is used to lower the pH in this tank to 4.5 and the slurry is held under these conditions for 5 h. Glucoamylase is added at 0.11% (db) during the saccharification step, and the starch is further hydrolyzed from dextrins into glucose at a temperature of 61 °C. During this incubation, almost all of the dextrins are converted to glucose although the glucoamylase continues to be active and can continue hydrolysis during fermentation if there are any unhydrolyzed dextrins remaining. Following the saccharification reaction, the slurry is transferred to the fermentation vessel with heat being recovered from the outlet stream, and cooled to 32 °C prior to fermentation.

Fermentation is the conversion of glucose to ethanol and carbon dioxide using yeast. The fermentation simulated in the process model is a batch process with six fermentors of approximately 1.9 million l (504,000 gal) each. The residence time is set at 68 h, with a working volume of 83% in the fermentors. Cooling is continuous as the conversion of glucose to ethanol produces 1200 kJ/kg of ethanol produced (516 Btu of heat per pound of ethanol) (Grethlein and Nelson, 1992). The extent of conversion is set according to experimental or process data, and the current fermentor output is 10.8% ethanol (w/w). A portion of the glucose (5 wt%) is converted into other solids (yeast cells). All of the reactions, volumes, residence times, agitation/pumping power required, and other operating parameters may be adjusted to imitate an existing fermentor or make use of experimental data, and the model will scale the unit to accommodate any change in raw material plant throughput.

The beer from the fermentation is heated using the process stream inlet to the saccharification tank, and then sent through a degasser drum to flash off the vapor. The vapor stream is primarily ethanol and water with some residual carbon dioxide. The ethanol and water vapors are then condensed and recombined with the liquid stream prior to distillation. Any uncondensed vapor is combined with the carbon dioxide produced during fermentation and sent through the carbon dioxide scrubber prior to venting or recovery.

2.3. Distillation and ethanol recovery

The first step in ethanol recovery is the beer column, which captures nearly all of the ethanol produced during fermentation. An almost equal amount of water is also distilled that must be separated from the ethanol in the next stage of rectification/stripping. The outlet from the bottom of the distillation column contains a considerable amount of water and non-fermentable material such as protein, oil, fibers, and residual chemicals unconsumed during fermentation.

Recovery of the ethanol from the beer column distillate is accomplished through the combined action of the rectifier, stripper, and molecular sieves. Over 99% of the ethanol goes out of the top of the rectifier as distillate. The remaining bottoms product is fed to the stripping column to remove additional water, with the ethanol distillate from stripping being recombined with the feed to the rectifier. The distillate of the rectifier, containing primarily ethanol, feeds the molecular sieves, which captures the last bit of water, creating 99.6% pure ethanol.

Molecular sieves are composed of a microporous substance, designed to separate small molecules from larger ones via a sieving action. Water molecules are trapped and adsorbed inside the microporous beads, whereas the larger ethanol molecules flow around them. The water produced when the molecular sieves are regenerated by heating in an offline operation, is combined with the process condensate stream used to slurry the incoming ground grain.

2.4. Stillage processing

A mixture of the non-fermentable material at 15% solids from the bottom of the beer column is fed to the whole stillage tank at the beginning of the stillage processing section. About 83% of the water present in stillage is removed during centrifugation, producing wet distiller's grains at 37% solids. The liquid product from centrifugation, known as thin stillage, is split and used as backset, with the rest going on to the thin stillage tank. Approximately 21,000 kg/h (6000 gal/h) of backset is fed back into the second step of the liquefaction process, with 59,000 kg/h (16,862 gal/h) remaining for thin stillage processing.

The thin stillage tank helps to maintain a constant feed to the evaporator, where water is recovered and the concentrate is dried further. The concentrate from the evaporator, at approximately 35% solids, is mixed with the wet distiller's grains coming from the centrifuge and sent to a large rotary drum dryer. The four-effect evaporator uses the overhead vapors from the rectifier instead of steam to provide heating for the first effect of the evaporator. The heated process streams are used in following effects of the evaporator. Outgoing vapor from the evaporator is condensed and mixed with the rest of the process condensate, which is used to slurry the ground grain at the beginning of the process. The drum dryer reduces the moisture content of the mixture of wet grains and evaporator concentrate from 63.7% to 9.9%, and this becomes the coproduct known as distiller's dried grains with solubles (DDGS). The volatiles produced during drying are treated with a thermal oxidizer prior to exhaust from the facility.

2.5. Final products

The main product, fuel ethanol, is produced after mixing the refined ethanol with approximately 5% denaturant (gasoline), and is held in the product tank prior to transport out for sale as a motor fuel additive. The simulated product rate of denatured ethanol is 119 million kg/year (39.9 million gal/year), or 0.422 l/kg (2.83 gal/bu). The DDGS produced is sold as an animal feed with its value based largely on protein content. The DDGS normally has a protein content of 27.8% and is produced at a rate of 119 million kg/year (131,000 metric tonnes/year).

3. Cost model description

The dry-grind cost model integrates data developed in the process model with current ethanol production cost information to allow the user to see the economic impact of modifications to the ethanol production process and products. The current ethanol cost information, which is based on equipment and operating costs and descriptions obtained from industry sources, was combined into an estimate of ethanol production costs using generally accepted methods for conducting conceptual technical and economic evaluations in the process industry (Jelen, 1970; AACE International, 1990; Dysert, 2003). The information in the model is not specific to a particular dry-grind plant but is representative of a modern facility. The plant operating costs are based on published material and utility costs and use salaries typical in rural central U.S. communities (Shapouri et al., 2003). Costs agree with actual ethanol production cost information collected in surveys conducted by the USDA (Shapouri et al., 2001).

Ethanol dry-grind plants operate 24 h/day, year-round, with time set aside for maintenance and repairs. A basis of 330 days per year (7920 h) operating time was used for this model, and the nominal capacity of the plant is approximately 45,200 kg/h (14 million bu/year) of corn.

3.1. Equipment costs

Process and equipment details vary from facility to facility as several technology suppliers provide the process design, equipment, and construction for ethanol facilities. Some facilities use stainless steel in their equipment whereas other facilities use carbon steel. In some facilities, steam is used to dewater the wet grains left after the ethanol is removed, while others use direct fired gas heaters, and a few organizations simply sell the grains wet. The pricing for the major process vessels in this study is based on stainless steel construction and information for specific pieces of equipment is included in the model.

The purchased costs for the major equipment items were based on budgetary quotations from equipment suppliers and erectors. In those instances where the capacities of the equipment in the model vary from the capacities for which quotations were received, the quoted costs were adjusted through the use of equipment/cost scaling factors. A discussion of the application of adjusting equipment costs to compensate for changes in capacities can be found in various publications (Jelen, 1970; Remer and Chai, 1990; Dysert, 2003). Other sources of equipment pricing that were used included Richardson's Process Plant Construction Estimating Standards (Richardson Engineering Services Inc., 2001), SuperPro Designer® and Chemcost® (Chemstations Inc., Houston, TX). Additional literature on the construction of ethanol plants is available as well (Henderson et al., 2005; Tiffany and Eidman, 2003; Bryan and Bryan International, 2003).

Additional equipment costs are included for the clean-in-place, plant air, and wastewater treatment systems that are not shown on the process diagram but are required. Data for the distillation column reboilers were included within the distillation unit operation, and were adjusted with information based on the Aspen Plus® simulation. The scaled energy requirement quantifies the energy requirements of distillation more accurately when calculating utility and equipment costs.

3.2. Feedstock costs

The primary feedstock for the facility is shelled corn. Enzymes to convert the starch in the corn to glucose, yeast to ferment the glucose into ethanol and carbon dioxide, gasoline for denaturing the ethanol, and small amounts of other feedstocks are also required. The volumes of materials required are provided by the process model and their unit costs have been incorporated into the model and can be easily modified as market conditions change. Pricing information for the various feedstocks is based on current published market prices and, information collected by federal agencies such as the USDA (Baker and Allen, 2004) and the Department of Energy (EIA, accessed November 2004).

3.3. Product values

Three products are produced in the conversion of corn to ethanol by the dry-grind process. They are ethanol, DDGS, and carbon dioxide. The denatured ethanol is sold as a commodity to distributors and normally blended with gasoline as a fuel oxygenate. Current pricing for it is readily available (Axxis Petroleum, 2005). The DDGS is sold as an animal feed and the market value is determined primarily from its protein content and the market pricing for other protein-based animal feeds. The carbon dioxide is often vented to the atmosphere since the cost of purifying and transporting to the end user, often outweighs any economic gains from selling it. In those cases where the carbon dioxide is collected and sold, the value to the ethanol producer is limited to US$ 5–17 per metric tonne. The normal practice would be to sell it to a third party at the plant site for purification and distribution. Our model does not include any income from the sale of the carbon dioxide but could easily be modified to do so.

3.4. Utility costs

Electricity, steam, natural gas, and cooling water are the utilities required in the process. Utility requirements of the various equipment operations are calculated and totaled within the program. These utilities are treated as purchased utilities and the unit costs for each of them can be easily changed by the user. Utility charges were estimated based on current market conditions. The price of steam was set at US$ 17.08 per 1000 kg. Natural gas prices are included at US$ 289 per 1000 kg (US$ 6.00/million Btu). An electric power cost of US$ 0.014 MJ^{-1} (US$ 0.05 kWh^{-1}) was also used in calculations. Cooling tower water is set at US$ 0.07 per 1000 kg. Because the utilities are treated as purchased items, the capital costs associated with their generation are not included in this assessment.

3.5. Capital costs

The capital cost of the facility has been developed from the costs of the individual equipment items and

Table 3
Estimated capital costs for dry-grind ethanol facility

Section	Capital cost (US$ million)
Grain handling and milling	3.4
Starch to sugar conversion (liquefaction and saccharification)	5.3
Fermentation	10.5
Ethanol processing	8.0
Coproduct processing	17.8
Common support systems	1.7
Total	46.7

installation factors are given in Table 3. Industry feedback has led us to use a capital cost that is approximately three times the sum of cost of the purchased equipment. This represents the cost of the processing unit and does not include costs for items such as laboratories, office buildings, or railroad tracks to the facility. Working capital and cost of money during construction are not included in the capital equipment costs.

The capital equipment cost includes an allowance of US$ 1,800,000 to cover the cost of a plant air handling system, a clean-in-place system, and a wastewater treatment system that is necessary for the operation of the process but is not modeled in this program.

3.6. Annual production and unit costs

Annual ethanol production costs are calculated by summing the raw material and utility costs, charges for the facilities plant operators, maintenance and supervisory labor, operating and maintenance supplies, allowances for insurance and local taxes, an allowance for depreciation, and subtracting a credit for the sale of coproducts (Table 4). The unit production costs are calculated by prorating the annual operating costs, including an allowance for depreciation of the facility. A breakdown of annual production costs shows that the unit production cost of ethanol with the data used in this model is approximately US$ 0.27 l^{-1} (US$ 1.04 gal^{-1}).

3.7. Sensitivities

Shelled corn, the primary feedstock cost, has the greatest impact on the cost of producing ethanol. For the model presented, a corn price of US$ 0.0866 kg^{-1} (US$ 2.20 bu^{-1}) was used (Renewable Fuel News, 2004). In the past few years, the cost of corn has varied from less than US$ 0.0787 kg^{-1} to US$ 0.197 kg^{-1} (US$ 2 bu^{-1} to almost US$ 5 bu^{-1}). The impact of the cost of corn on ethanol production cost is shown in Fig. 2.

Table 4
Annual operating costs for producing 119.1 million kg/year of ethanol

	US$/year
Raw materials	
Corn	31024000
Denaturant	1038000
Enzymes	2016000
Yeast	477000
Other	496000
Utilities	
Electricity	1063000
Steam	5054000
Natural gas	3222000
Cooling water	922000
Labor and supplies	
Plant operations	1037000
Maintenance	1315000
Insurance and administration	722000
Depreciation (10 years straight line)	4664000
Subtotal	53050000
Coproduct credit	−11742000
Net annual production cost	41308000

An increase in the cost of corn causes a direct increase in the cost of ethanol production.

Changes in the composition of the feed also greatly impact the cost of ethanol production. A simple exercise in reducing the starch content of the incoming corn from 59.5% to 55% negatively impacted the amount of ethanol produced while also significantly affecting the DDGS. Denatured ethanol production dropped from 151 million l/year to 140 million l/year (2.83 gal/bu to 2.62 gal/bu) using the lower starch corn. The starch, which was replaced with non-fermentable polysaccharides, led to an increase from 119.7 million kg/year to 133.5 million kg/year in the amount of DDGS produced.

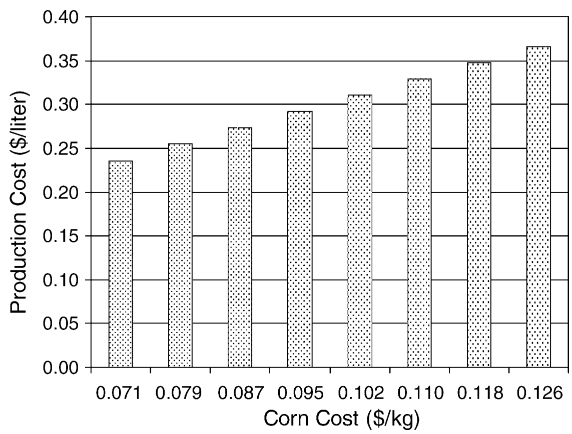

Fig. 2. Effect of corn price on ethanol production.

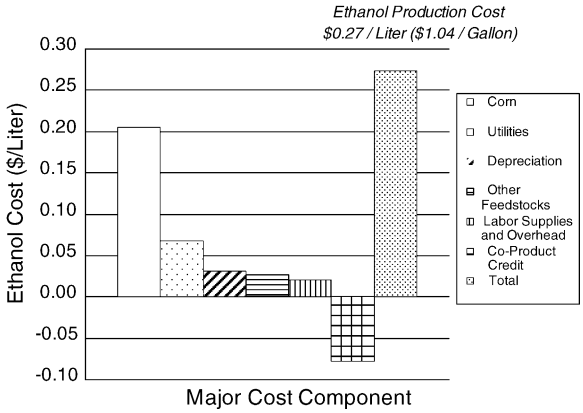

Fig. 3. Ethanol production cost breakdown.

The DDGS produced from corn with reduced starch content contained less protein, 24.7% versus the original 27.8%, which would impact the sale price of the new DDGS. In reality, the composition may not only exchange starch for non-starch polysaccharides, but the point of the exercise is made by showing the impact of a small change in composition.

Income from the sale of the DDGS coproducts reduces the ethanol production costs, and is a major factor in production costs. Electricity, natural gas, and steam costs also have a major impact on ethanol production economics. The breakdown of the costs to produce ethanol with the values we are using in the base-case model is illustrated in Fig. 3. Deviations from this model through changes in raw material price, feedstock composition, utility costs, or process modifications may be evaluated against this base-case scenario to determine their significance.

4. Conclusion

The process model developed here reflects the base case for a 40 million gal/year fuel ethanol plant. By introducing changes to the base-case equipment, feedstocks, or utilities, it may be used to determine new capital and operating costs. The ability to compare a modified process with the base-case model will help researchers develop novel milling and ethanol production technologies.

4.1. Model availability

This model is available on request from the authors for non-commercial research and educational uses to show the impact on ethanol production costs of changes in the process and coproducts of the ethanol from starch process. It is not intended to replace a customized process design package. The model resides on a file which requires the use of SuperPro Designer® Version 5.5, build 17 or later. A free evaluation copy of this program can be used to view the model and may be downloaded from the Intelligen website (www.Intelligen.com).

Disclaimer

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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